

Top Physics at ATLAS and CMS

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The potential for top quark physics of the ATLAS and CMS experiments at the Large Hadron Collider is surveyed ranging from top quark “re-discovery” and its use as a calibration tool to initial and later stage measurements.

1 Introduction: top quark at the LHC

ATLAS¹ and CMS² are complementary multi-purpose detectors aimed at measuring the properties of leptons, hadrons and photons in proton-proton (pp) collisions at the Large Hadron Collider³ (LHC). On its way to reach the design center-of-mass energy ($\sqrt{s} = 14$ TeV) and instantaneous luminosity ($L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), in 2009-2010 the LHC is expected to run at $\sqrt{s} = 10$ TeV, delivering an integrated luminosity ($\int L dt$) of the order of 0.2 fb^{-1} .³ All results reported in this paper are derived from simulated collisions at $\sqrt{s} = 14$ TeV.

At LHC with $\sqrt{s} = 14$ TeV top quark pair ($t\bar{t}$) production cross section⁴ ($\sigma_{t\bar{t}}$) is about 900 pb with a theoretical uncertainty of order 10% and a resulting rate of about 0.9 Hz already at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The single top quark production⁵ is dominated by t -channel diagrams that account for about 76% of the total cross section (σ_t) of about 320 pb. For LHC with $\sqrt{s} = 10$ TeV, $\sigma_{t\bar{t}}$ drops⁴ to ≈ 400 pb and, while σ_t remains about three times smaller than $\sigma_{t\bar{t}}$, the relevant $W+n$ jets background cross section (with $n>1$) decreases by $\approx 23\%$: this results into a somewhat worse signal to background ratio (S/B) for $t\bar{t}$ in comparison to $\sqrt{s} = 14$ TeV.

As the top quark decays to a W boson and a b -quark with a branching fraction (BR) of almost 100%, the $t\bar{t}$ final state features a b -jet pair associated with high transverse momentum (p_T) light jets when each W boson decays to quarks (fully hadronic channel with $BR \approx 44.4\%$) and one (ℓ +jets channel with $BR \approx 44.4\%$) or two high p_T lepton(s) ($\ell\ell$ channel with $BR \approx 11.2\%$) and sizeable transverse missing energy (E_T^{miss}) in the cases where one or two W bosons decay to leptons respectively. The final states of single top quark and $t\bar{t}$ can be obtained from

one another by swapping one $t \rightarrow Wb$ leg of the $t\bar{t}$ decay with a W boson (Wt channel) or one/two quarks (s and t -channels), one of which is a b -quark. The two final states then have similar backgrounds (single bosons (W , Z) plus jets, di-bosons and Quantum Chromodynamics (QCD) multi-jet events) and they are background to each other.

2 Re-discovering Top

A clean and robust analysis is required to re-establish the top quark signal with early data.

An example CMS analysis⁸ uses a realistic first day simulation of the detector mis-calibration and misalignment. The distinguishing features of the ℓ +jets final state (one central high p_T muon (μ) and four or more central high p_T jets) are coupled to additional μ isolation cuts (on energy deposited in a calorimeter cone around the μ and the μ spatial distance from the closest jet) to achieve a drastic reduction of the large QCD background. With only $\int Ldt = 10 \text{ pb}^{-1}$ the $t\bar{t}$ signal is expected to emerge from the background in the high jet multiplicity bins ($N_{jets} \geq 4$) with about 130 signal events and $S/B \approx 1.4$ as shown in figure 1 (left). No b -tagging or E_T^{miss} cuts are used. The size and shape of the QCD background have large uncertainties and its data-driven determination is a crucial ingredient in the analysis.

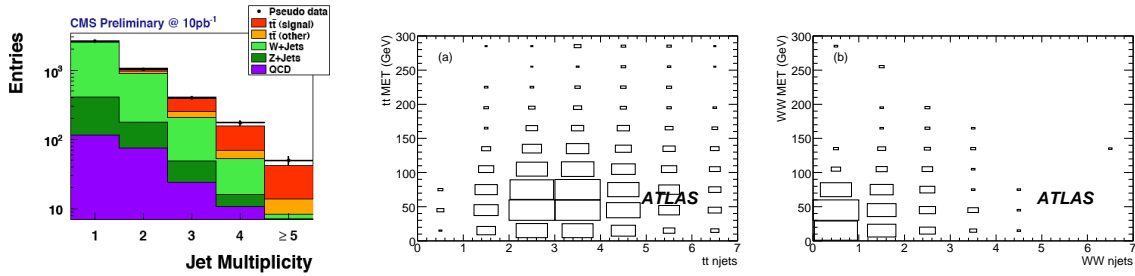


Figure 1: Left: CMS reconstructed jet multiplicity distribution for $t\bar{t}$ events passing the final selection with CMS detector except for the requirement $N_{jets} \geq 4$. Center and Right: simulated $e\mu$ templates in the plane of E_T^{miss} and number of jets for $t\bar{t}$ and W +jets samples as seen by the ATLAS detector. See text for references.

Once the signal is established, the lower $BR \ell\ell$ final state provides a clean sample to measure $\sigma_{t\bar{t}}$.^{9,10} The selections of both ATLAS and CMS require two high p_T isolated leptons with opposite charges and large E_T^{miss} that is not collinear with any of the two leptons or with the leptonic system. In an example from ATLAS $\sigma_{t\bar{t}}$ is derived even without any additional cuts (no b -tagging) by a likelihood fit of the signal to simulated templates of distributions in the E_T^{miss} -jet multiplicity space.^a As one can see in figure 1 (center and right), $t\bar{t}$ events show higher multiplicity and somewhat higher E_T^{miss} than W +jets background. With $\int Ldt = 100 \text{ pb}^{-1}$ such an analysis^{9,10} has an outstanding significance (≈ 20) which is already ≈ 7 with $\int Ldt = 10 \text{ pb}^{-1}$: the $\ell\ell$ channel can also be used to establish the $t\bar{t}$ signal. For $\int Ldt = 100 \text{ pb}^{-1}$ the ATLAS fractional uncertainty on $\sigma_{t\bar{t}}$ ($\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$) shows comparable systematic and statistical contributions (7% and 4% respectively).^b The crucial analysis requirements are to validate the E_T^{miss} description and perform data-driven background estimates.

The more statistically powerful ℓ +jets channel ($\ell = e, \mu$) is also used to extract $\sigma_{t\bar{t}}$ by requiring one high p_T central lepton and four or more central high p_T jets. The reconstruction

^aOther methods use additional cuts on the number of jets and their transverse momentum to purify the sample. With no b -tagging the cross section is extracted by counting the events in multiplicity bins or performing a likelihood fit to angular variables (ATLAS)⁹ while the use of b -tagging and W mass constraint can also be added (CMS).¹⁰

^bCMS estimates that for $\int Ldt = 1 \text{ fb}^{-1}$ the statistical contribution is expected to drop to 0.9% compared to a dominant systematic contribution of $\approx 11\%$ (see section 8.1.2 of ⁷).

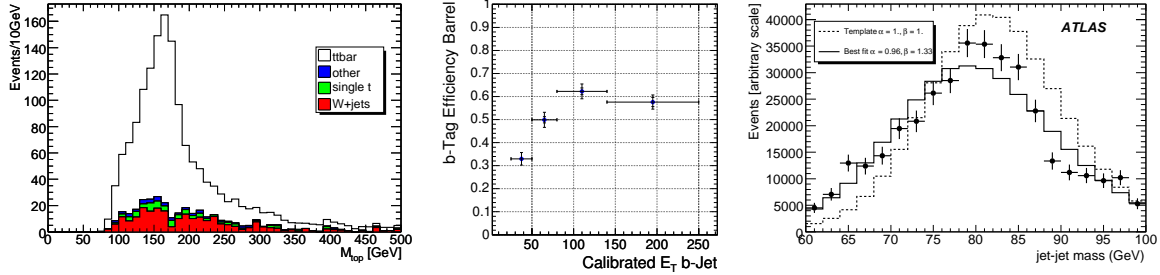


Figure 2: Left: ATLAS reconstructed top quark mass after W boson mass constraint for semi-leptonic ($\ell = e$) analysis. Center: CMS b -tagging efficiency measurement as a function of the jet E_T for jets in the barrel ($|\eta| < 1.5$). Right: ATLAS di-jet invariant mass in fully simulated $t\bar{t}$ events (dots) superposed on the template histogram with $\alpha = 1$ and $\beta = 1$ and the best fit histogram. See text for references.

of the hadronic top is used to enhance the signal over the dominant W +jets background when no b -tagging is used. Figure 2 (left) shows the ATLAS result⁹ for $\int Ldt = 100 \text{ pb}^{-1}$ where the hadronic top consists of the three jets with the highest total p_T and at least one di-jet pair is required to have a mass consistent with the W boson.^c Then $\sigma_{t\bar{t}}$ can be extracted by a likelihood fit to the mass shape (ATLAS) or by simply counting events after subtracting the expected background (ATLAS, CMS). For $\int Ldt = 100 \text{ pb}^{-1}$ the ATLAS $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ in a robust counting experiment⁹ is already systematic-dominated ($\approx 17\%$ compared to 3% statistical contribution). The main initial systematic uncertainties are the jet energy scale (JES) and the normalization of the W +jets background which, like the estimate of the uncertain QCD background, benefits from a data driven approach. A precise (5%) measurement of the b -tagging efficiency will be necessary for it to be used effectively in the cross-section measurement.

3 Top for Calibration

The established ℓ +jets sample can be used (together with the di-lepton (CMS)) to measure the b -tagging efficiency ϵ_b . By exploiting cuts on the kinematic and topological properties or by cutting on likelihood discriminants, it is possible to select a highly enriched b -jet sample in which, after background subtraction, ϵ_b can be measured¹¹, also as a function of the b -jet pseudo-rapidity and transverse energy (E_T) (also see section 12.2.8.1 of²). CMS shows an example of this determination in figure 2 where ϵ_b is shown to vary from 30% to 60% in the E_T range (50 GeV, 250 GeV) for the barrel section using $\int Ldt = 1 \text{ fb}^{-1}$. With $\int Ldt = 1 \text{ fb}^{-1}$ an uncertainty on ϵ_b of 6% in the barrel and of 10% in the endcaps is expected.^d ATLAS showed that a global average ϵ_b can be known at the 5% level with $\int Ldt = 100 \text{ pb}^{-1}$ by performing a likelihood fit to the expected number of events with zero to three b -tagged jets¹¹ (ϵ_b , the c -tagging efficiency and $\sigma_{t\bar{t}}$ are determined simultaneously).

Once b -tagging is understood the ℓ +jets sample can be used to identify the b and the W di-jet system that result from the “hadronic” top decay (for high p_T jets). In this way in ATLAS the global average JES for light jets is expected to be known at the 2% level even with 50 pb^{-1} by performing a χ^2 fit to di-jet mass simulated templates when varying the overall light jet scale (α) and resolution (β) with respect to the default.¹¹ An example of such technique is shown in figure 2 (right). Differential information on the light JES can be known at about 2% with $\int Ldt = 1 \text{ fb}^{-1}$ by using re-scaling techniques¹¹, while CMS expects that exploiting the top quark

^cThe addition of one or two b -tagged jets improves S/B⁹ (ATLAS) and with two b -tagged jets and cleanly separated jets, a convergent kinematic fit imposing the W mass constraint to the light di-jet system can be used to select events (see section 8.1.3 of⁷) (CMS).

^dA 10% uncertainty is expected by ATLAS for $\int Ldt = 100 \text{ pb}^{-1}$.

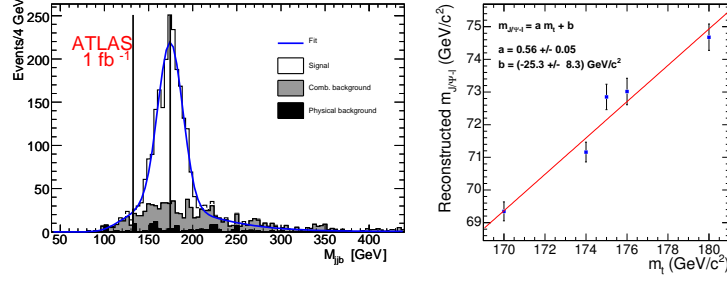


Figure 3: Left: ATLAS reconstructed hadronic top quark mass fitted with the sum of a Gaussian and a “threshold” function, scaled to $\int Ldt = 1 \text{ fb}^{-1}$. Right: correlation between the CMS reconstructed three lepton invariant mass and the top input mass at full simulation. See text for references.

mass measured at the Tevatron can provide knowledge of the average b JES¹³ at the % level with $\int Ldt = 100 \text{ pb}^{-1}$.

4 Measuring Top

4.1 Top Quark Mass

Equipped with better understanding of b -tagging and JES, the top quark mass (m_{top}) can be measured in the ℓ +jets channel by using the same selection required for $\sigma_{t\bar{t}}$ measurements and requesting at most harder jets (ATLAS) to suppress backgrounds. The hadronic W is reconstructed even with minimal or no b -tagging information and it is then associated with the closest jet or b -jet by its spatial (ATLAS) or kinematic (ATLAS/CMS) distance.^{14,15} The top quark mass value is then derived by either fitting an analytic function (ATLAS), extrapolating or performing a more sophisticated event-by-event likelihood fit (CMS). An example from ATLAS is shown in figure 3: after b -tagging, a nearly background-free scenario is obtained where the reconstructed top mass is fitted by a Gaussian plus a “threshold function”.¹⁴ The measurement is quickly systematics dominated, mainly by the jet energy scale (particularly the b -jet scale). A top quark mass uncertainty of the order of 1 to 5 GeV is expected to be achievable^{14,15} with $\int Ldt = 1 \text{ fb}^{-1}$ if the uncertainty on the JES is in the range of 1% to 5% respectively. The fully hadronic and $\ell\ell$ channel also have mass information, but the extraction is harder due to the increased level of combinatoric background and the final state neutrinos.^e

Alternative techniques to measure the top quark mass are also considered to reduce the impact of JES systematic uncertainty. In an example from CMS¹⁶, ℓ +jets events are sifted through to find exclusive b -jet decays to J/Ψ (with the b -jet coming from $t \rightarrow Wb \rightarrow \ell\nu b$ chain). The top quark mass is strongly correlated with the mass of the system formed by the J/Ψ and the lepton from the “leptonic” top decay as it is shown in the calibration curve by CMS in figure 3. The systematic uncertainty is dominated by theoretical contributions (mainly from models of b -quark fragmentation and underlying event) while the JES contribution is negligible. Given the low BR rate for $t\bar{t}$ event to produce a final state with a leptonic J/Ψ ¹⁶, a top quark mass uncertainty of about 2 GeV is expected for $\int Ldt = 20 \text{ fb}^{-1}$.

4.2 Single top quark

Once the $t\bar{t}$ signal is established and measured, the attention can turn to measuring σ_t in the dominant t -channel where one top quark decays leptonically (the final state is then $q\ell\nu b(b)$).

^eFor instance CMS expects¹⁵ top quark mass uncertainties of about 1.2 GeV in the $\ell\ell$ channel with $\int Ldt = 10 \text{ fb}^{-1}$ and 4.2 GeV in the fully hadronic channel with $\int Ldt = 1 \text{ fb}^{-1}$.¹⁵

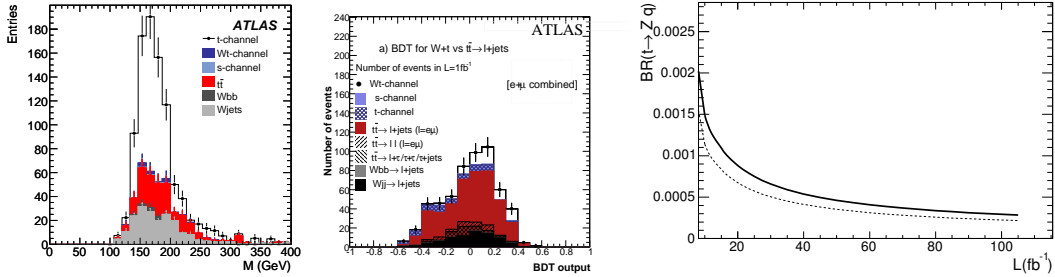


Figure 4: Left: ATLAS reconstructed leptonic top quark mass distribution with cut on BDT output of 0.6. Center: ATLAS reconstructed distribution for BDT against $t\bar{t}$ in the ℓ +jets channel in the 3 jets final state analysis for $\int L dt = 1 \text{ fb}^{-1}$. Right: branching ratios of an FCNC signal detectable by CMS at the 5 s.d. level as a function of the integrated luminosity for the qZ channel, shown with (solid line) and without (dashed line) systematic uncertainties. See text for references.

In an example from ATLAS,¹⁷ a complex set of kinematic cuts (on the final state lepton, the b -jet and the distinctive single forward light jet) is coupled to a multivariate Boosted Decision Tree (BDT) based on a set of shape variables to separate the signal from the background. The distribution for the top quark mass after all cuts for $\int L dt = 1 \text{ fb}^{-1}$ is shown in figure 4 (left) where the single top signal is standing out of the remaining $t\bar{t}$ and W +jets backgrounds. With these techniques S/B is expected to be about 1.3 with $\delta\sigma_t/\sigma_t$ dominated by systematic contributions even for $\int L dt = 1 \text{ fb}^{-1}$. Given the sizeable background to be overcome, the $t\bar{t}$ signal knowledge from the data is required in addition to the W +jets and the QCD signals. In addition an excellent detector understanding is required (b -tagging performance, JES) also to control the BDT inputs.

The less statistically powerful Wt channel is very similar to the $t\bar{t}$ signal in its final state (one b -jet less). So, as ATLAS shows in figure 4 (center), even after cuts on a set of kinematic variables and a set of BDT outputs based on twenty-five variables, the $t\bar{t}$ background is still sizeable¹⁷. This results into an expected S/B of about 0.4 with $\int L dt = 1 \text{ fb}^{-1}$. Only a few fb^{-1} will allow three standard deviation (s.d.) evidence to be established and a measurement of the cross section with a relative uncertainty of 20% should be in sight with 10 fb^{-1} . The lowest BR s -channel is expected to be the most difficult: ATLAS, for instance, expects to achieve a 3 s.d. evidence¹⁷ with about 30 fb^{-1} .^f Even more than for the t channel, both s and Wt channel will require an excellent detector understanding to be coupled to data-driven background estimation techniques and to a good control of the theoretical description of initial and final state radiation (particularly for the Wt channel whose similarity to $t\bar{t}$ makes it more sensitive to jet multiplicity).

5 Top beyond the standard model

Measurements of the properties of the top quark offers a window onto possible physics beyond the standard model. An example from CMS¹⁹ shows the sensitivity to Flavour Changing Neutral Current events where a $t \rightarrow Wb$ leg of the $t\bar{t}$ decay is replaced by a $t \rightarrow Zq$ decay. The resulting final state is $\ell\ell q\bar{q}l\nu b$. Cuts are applied to all the expected final state particles: one b -tagged jet, one light jet and two isolated opposite-sign leptons whose di-lepton mass is consistent with the Z boson. Additional cuts on the masses and the angular relation of the Zq and Wb systems tend to select events consistent with a $t\bar{t}$ decay. Once the background is subtracted (mainly $\ell\ell t\bar{t}$ events) it is possible to count the events and measure the cross section. Figure 4 (right) shows the cross sections for which a 5 s.d. sensitivity is expected as a function of the collected

^fCMS expects to need at least 10 fb^{-1} to measure the cross section with a systematic-dominated uncertainty of about 30%.¹⁸

integrated luminosity. With $\int L dt = 10 \text{ fb}^{-1}$ a branching ratio of $1.49 \cdot 10^{-3}$ is expected to be detectable (see section 8.5.4 of⁷). The main systematic uncertainties derive from jet and lepton energy scale and b -tagging efficiency.

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14. See section *Top Quark Mass Measurements* of⁶.
15. See section 8.2.2 of⁷.
16. See section 8.2.4 of⁷ and references therein.
17. See section *Prospect for Single Top Quark Cross-Section Measurements* of⁶.
18. See section 8.4.4 of⁷.
19. See section 8.5 of⁷.